

**CLOSED-LOOP HABITATION  
AIR REVITALIZATION MODEL  
FOR REGENERATIVE  
LIFE SUPPORT SYSTEMS**

Final Report

NASA/ASEE Summer Faculty Fellowship Program--1991

Johnson Space Center

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Date Submitted:	August 9, 1991
Contract Number:	NGT-44-011-800

## ABSTRACT

The primary function of any life support system is to keep the crew alive. This means it must provide for breathable air, potable water, edible food and disposable waste. The interesting thing is that none of the chemical elements are ever used up. They just change from one molecular form to another. In a well-balanced or "regenerative" life support system, the various components are each using what is available and producing what is needed by other components so that there will always be enough chemicals in the form in which they are needed. There would be very little excess and there would never be a long-term build up of excess compounds.

Humans are not just users of the system, they are actually one of the participating components of the system. Since humans are involved, it is desirable for the system to be self-sustaining and independent of outside resupply. If this could be achieved then the original chemicals would be continually recycled and the humans would not be jeopardized by resupply schedules. This would make the system virtually a Closed-loop Habitation (CH). Our earth is one of the best examples of a CH. When we send astronauts on extended space voyages such as to the moon or Mars we would like to provide them with a scaled down miniature CH.

There are a number of inherent difficulties in trying to create a miniature version of our earthly CH. 1) Earth's size gives it sufficient mass and sufficient gravity to retain its atmosphere. A scaled down version must use artificial containment such as sealed enclosures. Thus it is subject to leakage. 2) The earth has a very large, very diverse and complex ecosystem that would be difficult to duplicate on a small scale. 3) The size of the earth's atmospheric buffers would be prohibitively massive in a proportionately scaled down version for even one person, much less an entire crew, on a space voyage. 4) Natural disasters such as violent weather or wildfire are necessary to the earth's ecosystem but would be hard to duplicate and difficult to manage on an isolated lunar or Martian outpost. The list goes on and on.

In a miniature CH we must provide a minimal structure and make up the difference by artificial components such as physicochemical systems that perform the conversions that the earth can achieve "naturally". To investigate the interactions of these components we have designed a computer model that simulates a miniature CH with emphasis on the air revitalization components. It is called the Closed-loop Habitation Air Revitalization Model (CHARM).

## INTRODUCTION

Present life support systems that rely heavily on expendable materials are becoming unattractive for extended space voyages (e. g. Moon or Mars). Strict mass and volume constraints make it necessary to consider regenerative life support systems as an alternative. Present technologies, including physicochemical and biological processes, have demonstrated the feasibility and potentials of regenerative life support at a component level. However, there is much work that remains to be done to advance the maturity of the technologies and to study integration of the regenerative life support components. NASA has identified regenerative life support technologies as one of the critical areas of research and development for space exploration. Not only does the success of the mission depend on life support, so does crew existence.

## METHODOLOGY

This investigation involves the development of a computer model that simulates the operation of the air components of a regenerative life support system. There are several modes in which the model can be run to aid the study of regenerative life support systems.

### Verification Mode

The model is run behind an actual life support system test bed that it models. In this mode the model can be used for any one or more of at least three different purposes:

- 1: to validate model correlation with test bed;
- 2: to corroborate test bed results; and
- 3: to understand and explain unexpected test bed results.

### Warning Mode

The model runs ahead of an actual life support system test bed that it models. In this mode the model can be used to predict what the test bed will do, thus eliminating any surprises that might occur. The researcher can then be ready with the extra equipment, supplies and procedures that might be necessary for the upcoming event.

### Preparation Mode

The model is run for many weeks testing the boundary conditions in preparation for the construction of a new test bed facility. This could save a great deal of expense in construction costs by making sure the new facility can handle all of the tests for which it is being designed.

### Investigation Mode

The model is run independently of any test bed facility. In this mode the model can run test for which there is no test bed available. Unexpected results could pinpoint areas for future investigation.

### Blanket Mode

The model runs large amounts of data to cover the gaps between the data values obtained from a test bed.

### Query Mode

The model can be used to search for particular nodes of confluence or the occurrence of particular events.

## PARAMETERS

One way to explain the operation of CHARM is to list all of the parameters and explain which ones can be varied and which ones must remain fixed and at what value.

### System Constants

These values are well known constants.

#### A. Atomic weights

(Based on IUPAC Atomic Weights of the Elements 1981)

- |             |   |          |
|-------------|---|----------|
| 1. Hydrogen | = | 1.00794  |
| 2. Carbon   | = | 12.01100 |
| 3. Nitrogen | = | 14.00670 |
| 4. Oxygen   | = | 15.99940 |

#### B. Conversion factors

(CRC Handbook 1987)

- |               |   |            |
|---------------|---|------------|
| 1. Lbs. to kg | = | 0.45359237 |
| 2. Ft. to m   | = | 0.3048     |

## Crops

- A. Any area ratio of the following four crops can be grown: lettuce, potato, soybean, wheat. The current area is  $9.75 \text{ m}^2$ .
- B. Growth characteristics are totally adjustable to obtain desired curve.
- C. Any amount of fallow area can be designated.
- D. Each crop can be set independently for any ratio of daylight vs night. This affects growing time, but growth curve must be set separately. Currently, potatoes have 24 hrs. daylight, others have 16 hrs.
- E. Each crop can be set independently for harvest time. Currently, lettuce is harvested in 30 days, potatoes in 160 days, soybean in 90 days, and wheat in 80 days.
- F. All crops are checked to maintain mass balance.

## Growth Chamber Parameters

- A. Volume is a variable affecting leakage. Current value is  $25 \text{ m}^3$ .
- B. Growing area is a variable. Current value is  $9.75 \text{ m}^2$ .
- C. Air pressure is a variable. Current value is 10.2 psia.
- D. Temperature is a variable affecting density. Current value is 20 degrees C.
- E. Light intensity is constant for each crop type:
  - Lettuce  $450 \text{ micro mol/m}^2\text{-s}$
  - Potato  $300 \text{ micro mol/m}^2\text{-s}$
  - Soybean  $700 \text{ micro mol/m}^2\text{-s}$
  - Wheat  $1200 \text{ micro mol/m}^2\text{-s}$
- F. When potatoes, soybeans and wheat are harvested, the inedible portion is discarded. When lettuce is cut, the inedible portion continues to grow new crop.

## Crew Cabin

- A. Volume affects leakage. Current value is  $30 \text{ m}^3$ .
- B. Crew number is variable. Current value is 1 person.
- C. Average crew weight is assumed to be 155 lbs. for diet.
- D. Energy usage is 2700 kcal/man/day for diet calculation.
- E. Crew diet is a variable. Current values are from the NIH recommended diet.
- F. Stored food is automatically used as needed.
- G. Uneaten edible portions of grown food is automatically computed, based on chosen diet, removed from system, and added to waste.
- H. All output is checked for mass balance.

## Buffers

- A. There are ten fluctuating variables that are tracked. They are: nitrogen, oxygen, carbon dioxide, water, hydrogen, methane, hydrazine, food, waste, and resupply.
- B. The volume of the gas storage buffers can be adjusted anywhere from zero to any positive real number.
- C. There are four sensor variables on each buffer. They are: empty, min., max., and full. Each can be adjusted individually as needed. The model is programmed to run physicochemical systems when values go out of the range between max. and min. The model will use resupply and auxiliary storage when values try to go below empty or above full.
- D. Besides the effect of the various components on the buffer levels, there is also provision for external factors that might affect the buffers. These can be used in addition to, in place of, or instead of the human component, the plants, or both.
- E. The variable leakage rate can be adjusted anywhere from 0 to 100 percent. All or a portion of the leakage can be made to reflect any of a variety of factors. These include the relative abundance of each atmospheric gas in the growth chamber and in the crew quarters separately along with the volume of each. It can also reflect the relative size of each molecule in case of permeable membrane type leakage, or each molecule leakage rate can be set individually.
- F. There are four physicochemical systems used by the system. They are:

Sabatier	$\text{CO}_2 + 4\text{H}_2$	$\rightarrow$	$\text{CH}_4 + 2\text{H}_2\text{O}$
O <sub>2</sub> generator	$2\text{H}_2\text{O}$	$\rightarrow$	$\text{O}_2 + 2\text{H}_2$
N <sub>2</sub> supply	$\text{N}_2\text{H}_4$	$\rightarrow$	$\text{N}_2 + 2\text{H}_2$
CH <sub>4</sub> burner	$\text{CH}_4 + 2\text{O}_2$	$\rightarrow$	$\text{CO}_2 + 2\text{H}_2\text{O}$
- These are controlled by the user by changing the buffer sizes mentioned above in B and C.
- G. The length of the calculation cycle can be varied to allow for more precise checking. The system currently operates on an eight-hour cycle.
- H. The program time span depends on the length of the calculation cycle in G above. On an 8-hour cycle, the program runs for one month. However, several consecutive months can be run at a time with perfect compatibility.
- I. There is an end-to-end mass balance check that can be performed to insure against unexplained loss or gain of mass throughout the program span.

## DISCUSSION

This program can produce data in a variety of graph and table formats. For most purposes, the preferred form is graphical. A few graphs have been included in this report to help illustrate the scope of CHARM. Figures 1 through 4 show the growth curves for four crops generated by CHARM. For this report we are using, with only minor adjustments, the formulas and data of Volk and Cullingford, "Crop Growth and Associated Life Support for a Lunar Farm," 1989.

Figure 5 is a graph showing the storage buffers of a system similar to the facility now producing lettuce in the "ten-foot chamber" at JSC. For this simulation, CHARM was provided with very large buffers. This prevents the built in physicochemical systems from going into effect, trying to keep the system in range. To produce this graph, the system grew lettuce on a 16 hour/day cycle of daylight vs. 8 hours of night for 30 days and then harvested.

The data in this graph, as in many of the others, reflect the amount of fluctuation in each compound. There is no indication as to how much of this variation is affecting the atmosphere or how much is being added to, or removed from the atmosphere as compensation for these internal changes. At the present time, because this information is not yet available, it is assumed that the atmosphere is remaining of constant composition and all variation occurs only in the storage buffers.

The system was arbitrarily assigned a leakage rate of 10% for carbon dioxide 5% for oxygen, and 5% for water vapor. The system was given a 0% leakage rate for nitrogen because the 10-foot chamber, being at ambient pressure on Earth instead of the airlessness of space, has about the same amount of nitrogen leaking in as it does leaking out. This situation will change somewhat when the chamber is lowered to 10.2 psia. Then, more air will be leaking in than out. CHARM can also be run at negative leakage to simulate this result. For the present, the other gases, besides nitrogen, will have a tendency to leak out, however, since they are at higher concentration in the chamber than similar gases outside the chamber. Figure 6 is a graph similar to figure 5 but it represents a facility growing multiple crops. The fraction that each crop represents of the total growing area is given above the figure.

Several facts are apparent from figures 5 and 6. It can be seen that more oxygen is being produced by the plants than is being consumed by the human in the model. Secondly, the plants are using more carbon dioxide than is being produced by the human. Thirdly, and most surprisingly, the water level is going down. This only represents the chemically available water. Atoms from the water are being incorporated into living tissue in the plants faster than water is being produced by oxidation of food by the human.

## CHARM LETTUCE

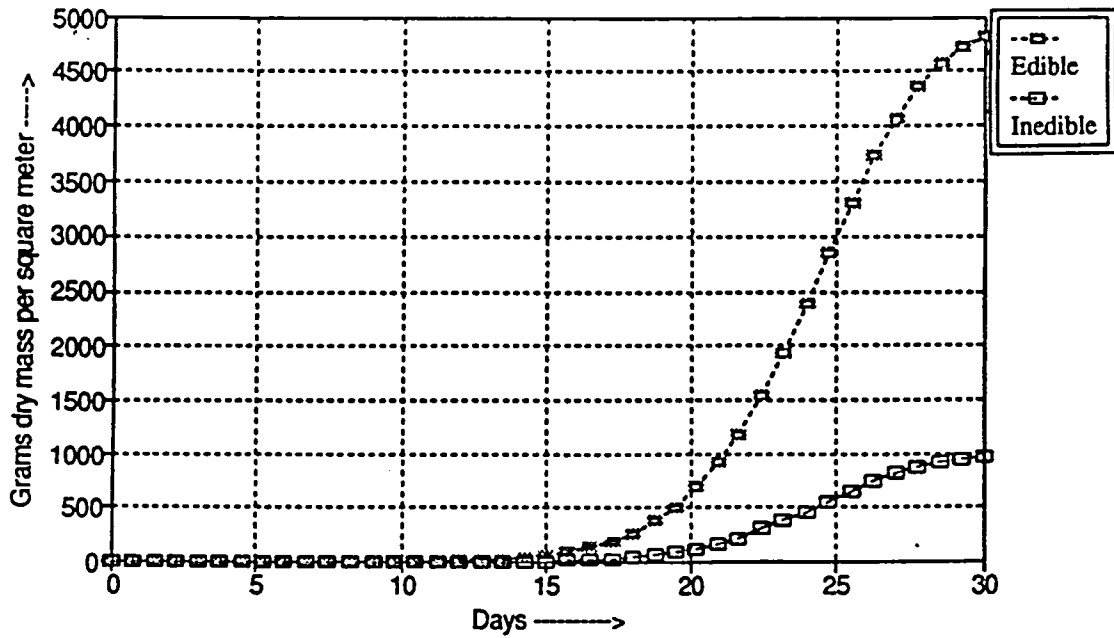


Figure 1.-Thirty day lettuce growth curves.

## CHARM POTATO

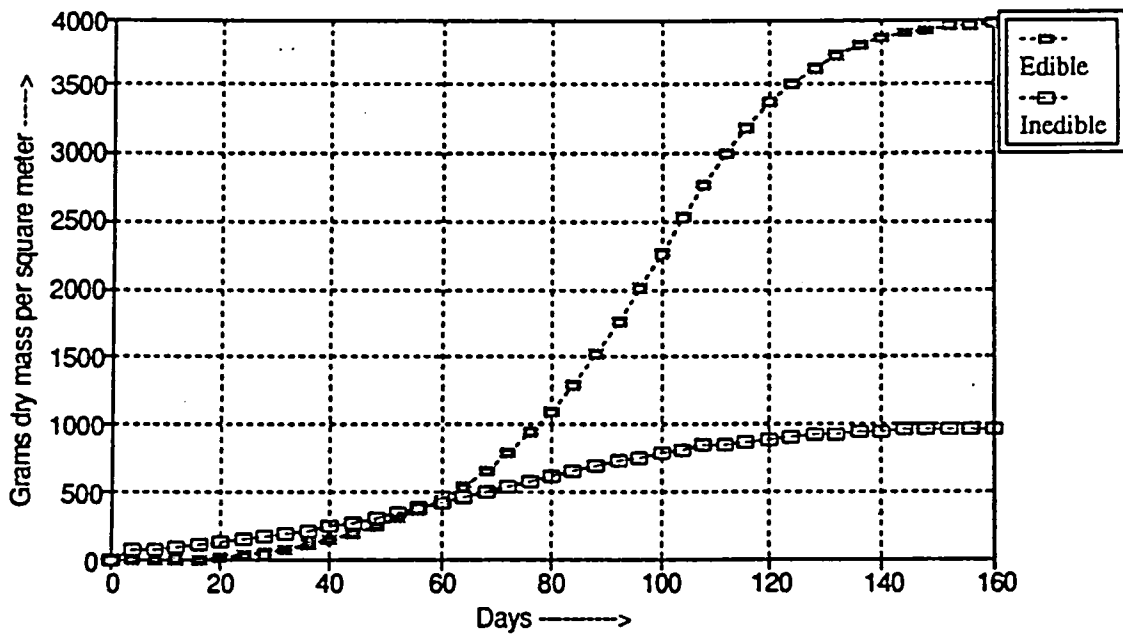


Figure 2.-One hundred sixty days of potato growth.



## CHARM SOYBEAN

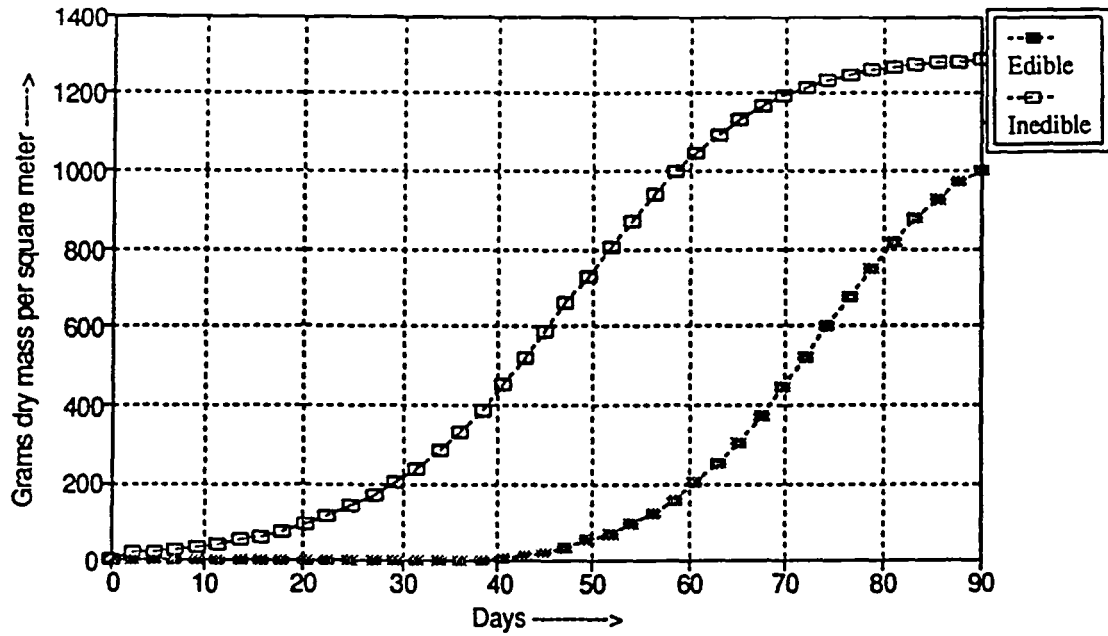


Figure 3.-Ninty day soybean growth curves.

## CHARM WHEAT

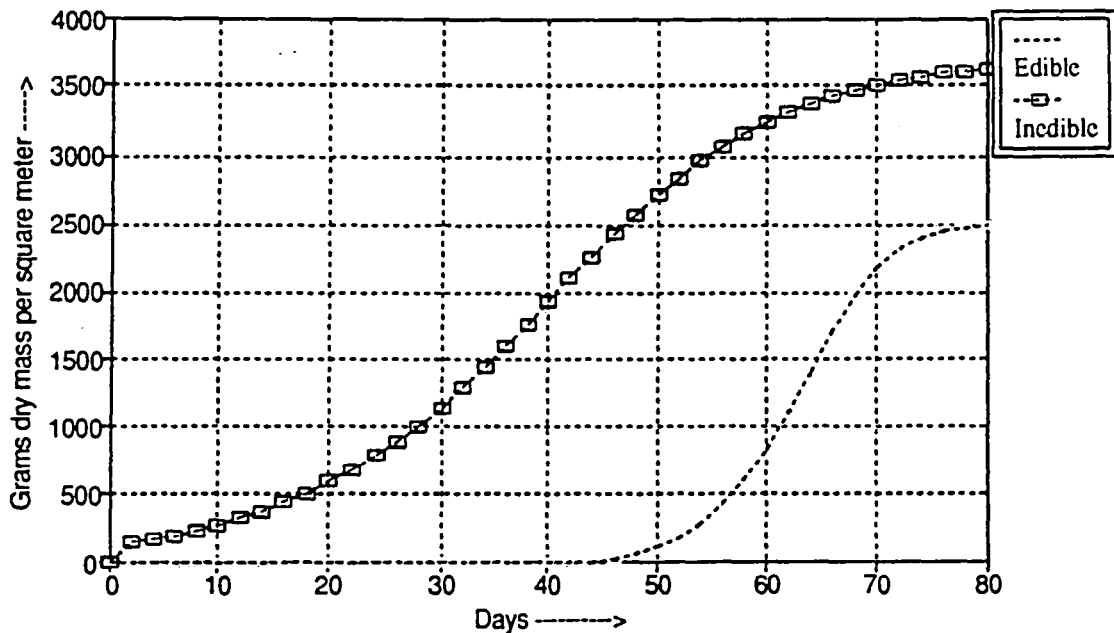
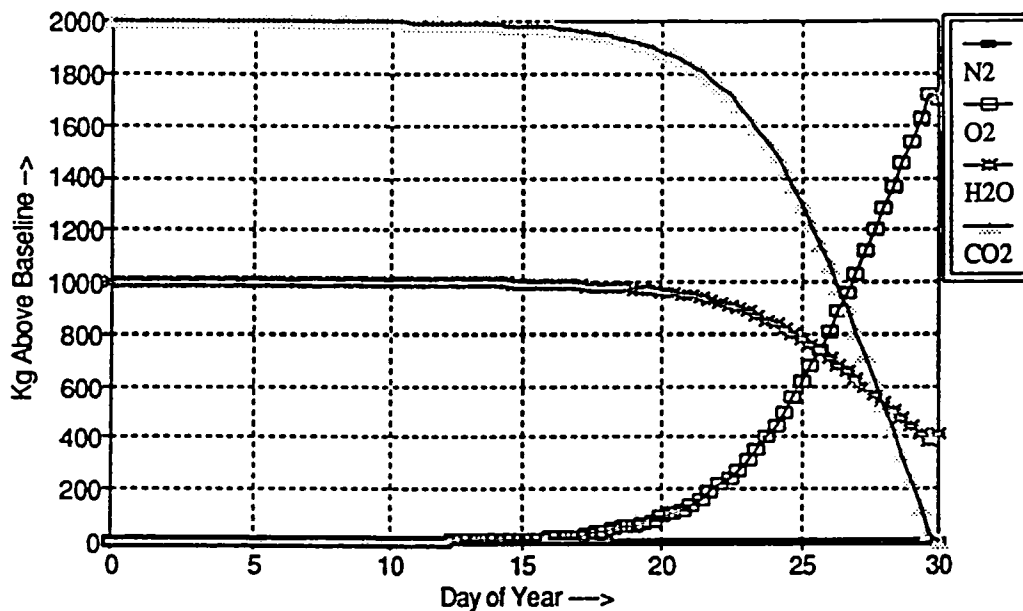


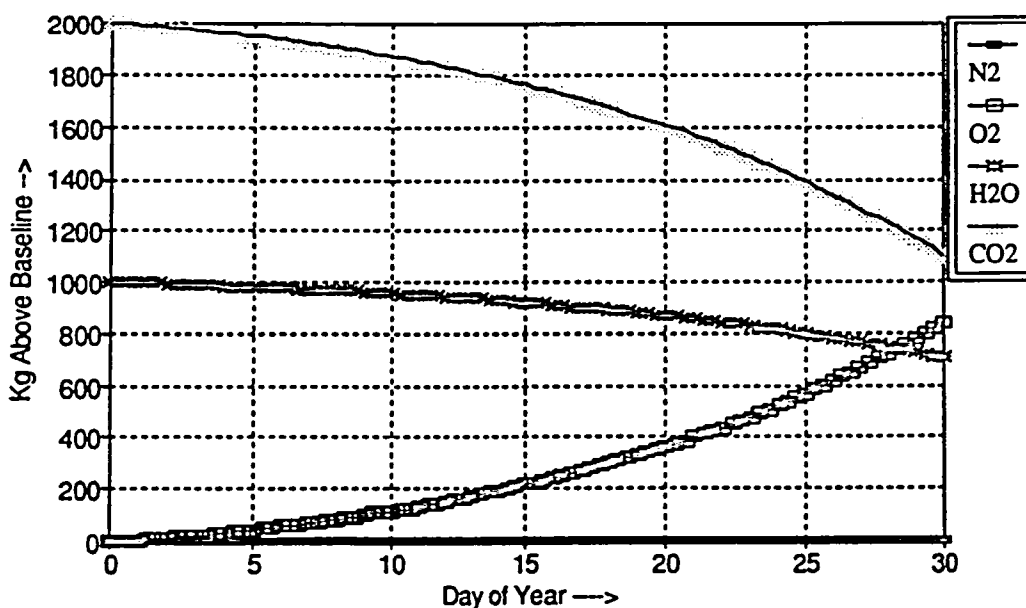
Figure 4.-Eighty day wheat characteristic curves.

**Crop Ratio: 1.0 Lettuce, 0.0 Potato, 0.0 Soybean, 0.0 Wheat**  
**Leak Rates: Nitrogen 1%, Carbon Dioxide 1%, Oxygen 1%, Water Vapor 1%**



**Figure 5.-Flux for 31 days of lettuce growth.**

**Crop Ratio: 0.0 Lettuce, 0.2 Potato, 0.7 Soybean, 0.1 Wheat**  
**Leak Rates: Nitrogen 1%, Carbon Dioxide 1%, Oxygen 1%, Water Vapor 1%**



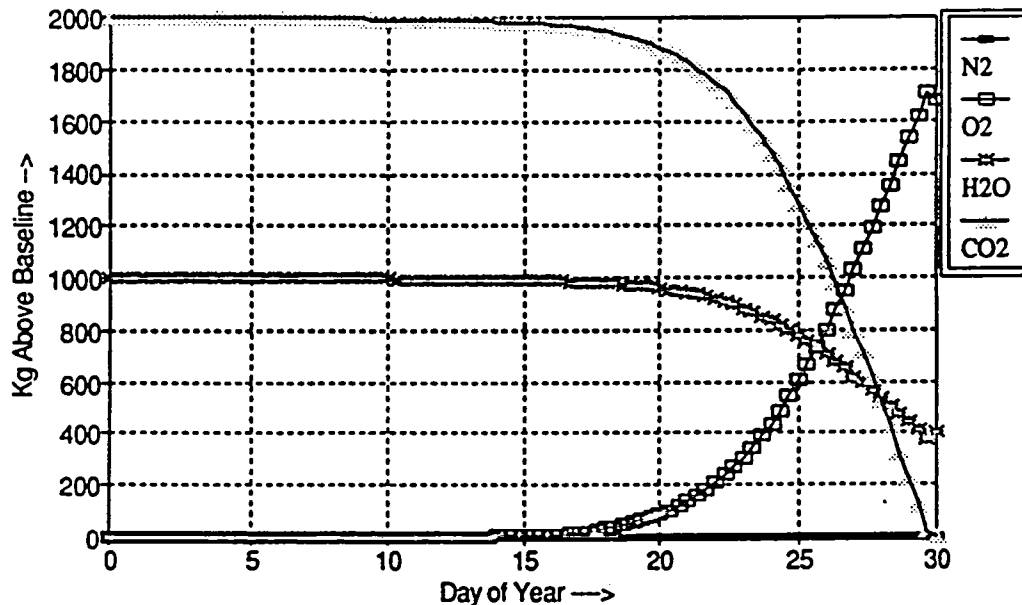
**Figure 6.-Flux for 31 days of multiple crops.**

Plants release a large amount of transpiration water into the atmosphere. This is a physical phenomenon which, although important, is not related to the chemical depletion of water by the plants. The missing component in this cycle is waste disposal. When left-over food, inedible plant mass and other waste is processed, some of the excess oxygen is consumed. Waste management also helps to make up some carbon dioxide and water losses. There is an inherent problem in the modeling of only one component of a complex system. The lack of a complete cycle makes verification difficult and somewhat questionable. One of the very nice features of CHARM is that it can easily be expanded to incorporate more components until it eventually models a complete regenerative life support system.

Figure 7 demonstrates the difficulty of the leakage question. In this example, 10% of the carbon dioxide is being lost per day compared to the rather low leakage rate of 1 percent for all of the other examples. Ten percent sounds very high because, at this rate, the carbon dioxide should be completely replaced every ten days. This is misleading. Compare the graph of figure 7 with that of figure 5. It is difficult to tell the difference. Actual leakage is 10% of only the atmospheric carbon dioxide. More carbon dioxide is in buffer storage. Storage buffers are assumed to be well sealed with hardly any leakage. Although the nominal rate may be 10% of atmospheric gasses or even higher, the effective rate on the system depends heavily upon buffer sizes. If storage buffers are a relatively small component of the total atmosphere, effects of leakage can be much greater. It sounds trite, but it is important to note: the more replacement mass you have in storage, the less you notice leakage. This is one of the factors that must be considered when deciding how large these buffers should be. If leakage in an actual test bed is high, this could make verifications difficult. Although it is easy to calculate how much has leaked, it is difficult to tell exactly when, where, and in what form it leaked. Many claims can be made with the assertion that any discrepancy is simply due to leakage. A computer model that simulates leakage can help to verify or refute some contentions.

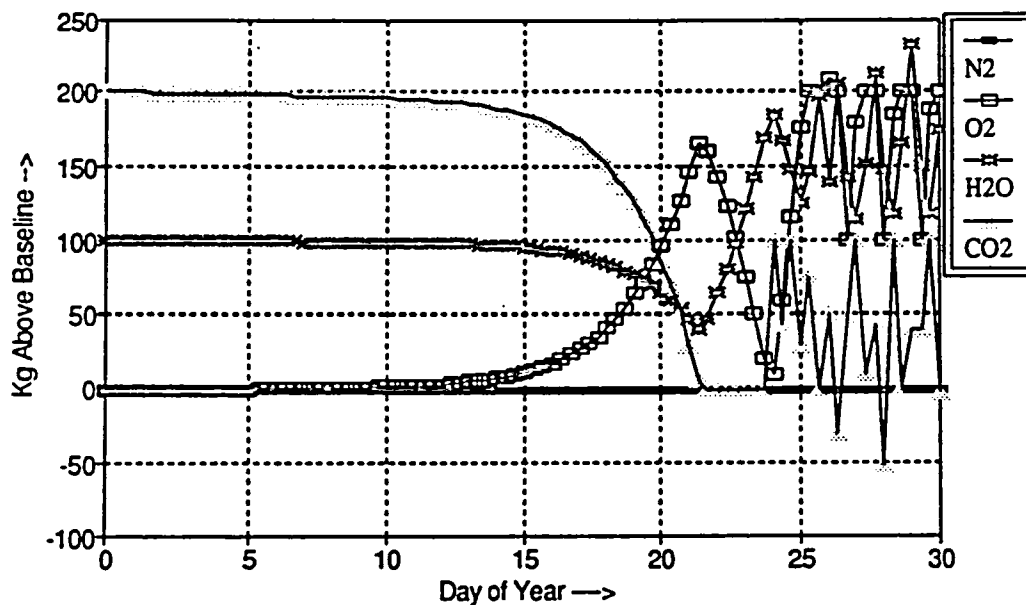
Figure 8 models a life support system similar to that for figure 5 except that the buffer sizes are much smaller. Automatic physicochemical systems try to keep the system operational between relative maximum and minimum values. Absolute boundaries of full and empty are maintained by processing and storage of excess supplies in other forms such as fuels and liquid water. Shortages are made up by use of resupply stockpiles. All processing and resupply is tracked and available for study. The interior, relative, boundaries are maintained by physicochemical systems as long as the necessary chemicals are available.

**Crop Ratio: 1.0 Lettuce, 0.0 Potato, 0.0 Soybean, 0.0 Wheat**  
**Leak Rates: Nitrogen 0%, Carbon Dioxide 10%, Oxygen 5%, Water Vapor 5%**



**Figure 7.-Moderato leakage rate.**

**Crop Ratio: 1.0 Lettuce, 0.0 Potato, 0.0 Soybean, 0.0 Wheat**  
**Leak Rates: Nitrogen 1%, Carbon Dioxide 1%, Oxygen 1%, Water Vapor 1%**



**Figure 8.-Small buffer volumes.**

The final month of this summer project was spent in the development of a user interface for CHARM. The purpose of this interface is to make CHARM user friendly. It is desirable that this program be useable by someone who is not familiar with Quattro Pro and even by those who do not normally use a spreadsheet in their work. The framework for this interface was built into the program during initial development so that it was a simple matter of tying it all together into one coherent package. To accomplish this, three new programs were written. These will be described in the three following sections.

## Heading

This program introduces users to CHARM. It allows them to log on and determines if they are new users. This information is used in two ways. It is incorporated into the printed records along with the current date and time as a record for user reference. It is also used by the program to allow regular users to skip some of the constant messages and menus that only serve to slow down the program for those who no longer need them.

This program also contains the main menu. From this menu the user is able to choose the type of work to be done. The user can scroll through the menu by any of three methods: the space bar (down only), the arrow keys, or the mouse. As the user highlights a selection, a short description appears at the bottom of the screen. Once the decision has been made, the user has three methods of making the selection: highlight the selection and press the enter key, use the mouse and click on any entry even if not in highlight, or type the first letter of the selection (the first letter is in red, the rest are black).

When users finish particular tasks, program execution returns them to the main menu. The bottom choice on the menu allows users to exit the program and automatically logs them off. This feature of returning to the most recent menu is common in most of the other menus throughout the user interface except where there is no further need for some menu. In that case, the user is returned to the previous menu.

Another decision on the main menu allows the user to select which printer to use. The remaining choices, besides the ever present "Help" selection which allows the user to call up a help screen, have to do with deciding whether to do input, processing, or output. Each of these latter three selections also require the user to make other decisions about the type of input, processing, or output that is to be done. Much of this additional selecting is also handled by the "heading" program in a manner similar to that described above.

## Files

This is the second of the three human interface programs of CHARM. Its primary function is to shuttle the various files in and out of main memory. It determines exactly which files will be needed, opens the files and leaves them open just as long as necessary. If a file will no longer be needed, it is closed and removed from main memory to make room for other files. This function is very important because, if too many files are open at one time it will cause the program to terminate for lack of memory space.

With Quattro Pro it is not necessary to open a file when information must be retrieved from it. Every time a file is opened, it can be updated with all pertinent information from all other files, even if they themselves are not open. However, there are many procedures that require a particular file to be open. Of even greater importance, a file cannot be updated if it is closed. Therefore it is necessary to open a file and update it before it is used so that other files will not receive old data from a closed file that was not updated in time. It is the function of this "files" program to hand the user over to the "update" program when a file may contain old data. A special benefit of this opening and closing of files is that files are always being "saved" so that abnormal termination of the program or system failure will never result in much lost data.

## Update

It is the function of this program to update the files in the proper order so that no file ever receives old data. This program works in cooperation with the "files" program to guarantee data fidelity. This program also works with "files" in the area of data retrieval. As files are being updated, they become available for output such as in the graphing routines. This results in a considerable savings in time. Since the files must be loaded and unloaded anyway, it makes sense for the computer and printer to work in tandem so that the printer can be working at the same time that the computer is processing. Although more graphs are available and many more are possible, the program currently allows up to eleven different graphs to be printed for each month of data for the entire run of the experiment. The program even prints out a data sheet showing the current values of the user chosen parameters, the date and time of the run along with the name of the user. Once the user has chosen the variables, dates of the run dates of crop failure and graphs to be printed, the program will run for as long as it takes to print all of the graphs on the chosen printer. No additional user intervention is necessary except possibly supplying more paper to the laser printer.

## CONCLUSION

CHARM is incorporated within a spreadsheet, Quattro Pro. This aspect gives it some disadvantages. Because of its dependence on Quattro Pro, CHARM can only be used in the Quattro Pro environment. This limits its accessibility. CHARM also uses a very large amount of main memory. When used on a machine with limited memory, Quattro Pro must constantly move files in and out of disk storage. This slows down processing considerably. If CHARM were used on a system where it had access to 1M or 2M of memory it would be able to operate several magnitudes faster. Some operations which are now quite complex would become simple by comparison. This would allow even greater tasks to be performed which are now only barely imaginable. CHARM is also starving for data. There is so much more it could accomplish if it were fed information concerning the effects of varying other values not now incorporated into CHARM.

However, the result of developing CHARM from Quattro Pro is not at all unilateral. There are also some clear advantages. The most obvious advantage is its facility for relatively quick development and rapid changes in its structure right down to its very foundation. Because Quattro Pro is so well tested, readily available, and popularly used, it is virtually error free. This greatly increases reliability and versatility of any imbedded programs. CHARM runs very fast for this type and size of program and allows for many variable parameters. Parameters which are not, now a part of it can be added if the relationships are known. Some unknown relationships can be investigated by varying parameters to extrapolate from the overlapping relationships which are incorporated within CHARM. The prototype nature of this program within a spreadsheet belies its power and functional status. The entire program, actually nineteen separate spreadsheets and programs plus several other utility programs, was written in just six months of programming by a single programmer. This fact is a testament to its potential. It can only be imagined what could be incorporated into CHARM with sufficient input and continued mathematical enhancement. One final observation. It is probably fortunate that CHARM was not developed on a larger computer. If it had been, it would have incorporated all of the power of that machine and become a much more powerful program. But as a trade off, it would also have become dependent on that larger machine and therefore would no longer be compatible with any of the much more numerous computers which are widely available around the country. It is impossible to predict how many people will ever see or use this program, but as much effort as has gone into it, I do hope someone, somewhere will find a use for it. In any case, it has been a good experience and a great project. For more information please call Chin H. Lin 483-9126 or Donald L. Henninger 483-5034.